Physical and Numerical Simulations Study of Heat Input Dependence of HAZ Cracking in Nickel Base Superalloy IN 718

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Abstract

Physical and numerical simulations study of heat input dependence of cracking in the weld heat affected zone (HAZ) in a nickel base superalloy, IN 718, was performed. Gleeble thermo-mechanical physical simulation showed that increase in resistance to cracking with heat input is associated with enhanced hot ductility of the alloy. Numerical calculations by finite element analysis show that in addition to the improved hot ductility, reduction in the HAZ cracking with increase in heat input is also attributed to a decrease in the gradient of the thermally generated strain rate during weld cooling.

Keywords

Superalloy; HAZ; Ductility; Welding

Introduction

Alloy IN 718 is the most widely used precipitation strengthening nickel base superalloy for the fabrication of aero- and land-based turbine engine components [McCay 1991, Radavich 2005] due to its excellent oxidation and hot corrosion resistance and high strength at elevated temperature up to 650^{o}C [Shonozaki 1999, Luo 2002, Kang 2001]. In addition, IN 718 posses relatively good resistance to post-weld heat treatment (PWHT) cracking because of the sluggish precipitation kinetics of its primary strengthening phase Ni_3Nb, γ'' [Lingenfelter 1989, Boech 1969]. The ever increasing demand for efficiency of the aero- and land-based turbine engines components necessitates that superalloys are fabricated in intricate shape and design either by casting, forging or by joining. In addition, owing to their high cost, it is economically more viable to repair damage or service-degraded components than to replace them with new parts. Traditionally, during fabrication of new parts and/or repair of service-damaged components of turbine engines, fusion welding process has proved to be an economical and reliable means of joining. A recent trend in the aerospace, automotive and power generation industries is the drive to utilize high power beam density sources to rapidly produce deep, narrow and low heat input welds during components fabrication and repairs. Laser beam welding (solid state, fibre or gas) is an attractive and promising joining technique with respect to the achievement of these goals with high reliability and productivity necessary for industrial manufacturing system [Sehar and Reed 2002]. However, weldability of alloy IN 718 can be undesirably limited by the occurrence of cracking in the HAZ during welding [Vincent 1980, Thompson 1998, Krenz 2009, Thompson 1969] and the applicability of laser welding to IN 718 alloy has not been fully studied and understood. In general, the cause of cracking in the HAZ of welded joint of superalloys has been attributed to both metallurgical (grain boundary liquation) and mechanical factors (magnitude of stresses and strains generated during welding thermal cycle). Previous studies have showed that the occurrence of cracking in the HAZ can be significantly influenced by the magnitude of heat input during welding [Richard 1994, Idowu 2007]. The lower the magnitude of heat input the higher is the susceptibility to weld HAZ cracking [Krenz 2009]. The main objective of the present work is to perform physical and numerical simulations study to better understand heat input dependence of weld HAZ cracking in IN 718 superalloy. The results of the study are presented and discussed in this article.

Materials & Experimental

The chemical composition of wrought IN 718 superalloy material used in this work in weight % is

0.5Al, 0.9Ti, 5.4Nb, 17.9Cr, 2.9Mo, 17.6Fe, 0.05Mn, 0.05Si, 0.026C, 0.007P, 0.0014Mg, more than 0.007S, 0.04B, and balance nickel. Physical simulation test samples were machined from the as-received material by a numerically controlled wire electro-discharge machine (EDM) and subjected to pre-weld solution heat treatment (SHT) at 1050°C for 1 hour, followed by air-cooling. The heat treated samples were surface ground and properly cleaned to remove surface oxides before use. In order to carefully study and evaluate the influence of heat input on hot ductility of the material during non-equilibrium rapid heating, physical simulation was performed using Gleeble 1500-D Thermo-Mechanical Simulation System at a rapid heating rate of 150°C/second to peak temperature 1160°C. The test temperature, 1160°C, is significantly lower than the equilibrium solidus and solid state dissolution temperature of the constituent phases in alloy IN 718 [Wei-Di-Cao 2005]. Specimens were pulled to failure at the test peak temperature (stroke rate of 50 mm/ second) after held for specific holding times ranging from 0.5 seconds to 3 seconds. The hot ductility of the alloy at test temperatures was determined based on the reduction in area by measuring the initial and final gauge lengths in regions around the fractured surface with Vernier calipers. Mounted polished sections of the solution heat treated sample were etched by swabbing in a solution of 48g CuCl + 480 ml HCl + 40 ml H_2O. The microstructure of the heat treated sample was first examined by optical microscopy, using a ZEISS Axiovert 25 inverted-reflected light microscope, equipped with CLEMEX Vision 3.0 image analysis software. Higher magnification and more detail microstructural study including fractographic examination was carried out using a JEOL 5900 scanning electron microscope (SEM) equipped with an Oxford (Oxford Instruments, Oxford, United Kingdom) ultra-thin window energy dispersive spectrometer (EDS). Meanwhile, numerical simulation by two-dimensional thermal elasto-plastic finite element analysis was performed using ANSYS code to study and better understand the dependence of heat input on susceptibility of the superalloy to weld HAZ cracking.

Results and Discussion

Figure 1 shows a SEM micrograph of solution heat treated (SHTed) material with an average grain size of 100 ± 30 μm. The microstructure consists of primary MC carbides based on titanium and niobium rich carbides which have been previously reported to form in the alloy [Qian 2003, Hong 2008]. Needle like secondary delta (δ- Ni_3Nb) phase precipitates were not observed in the SHTed, material because the 1050°C solution heat treatment used is above the precipitation and solvus temperature of the δ phase precipitates. The δ phase precipitates would normally form in the material by solid-state precipitation reaction during heat treatment in the temperature range 860-995°C [Janaki 2006]. The MC carbide precipitates were uniformly dispersed along grain boundaries and within grain interior. Furthermore, the main strengthening phase of the alloy, γ′′ precipitates, were not observed in the SHTed alloy by the SEM.

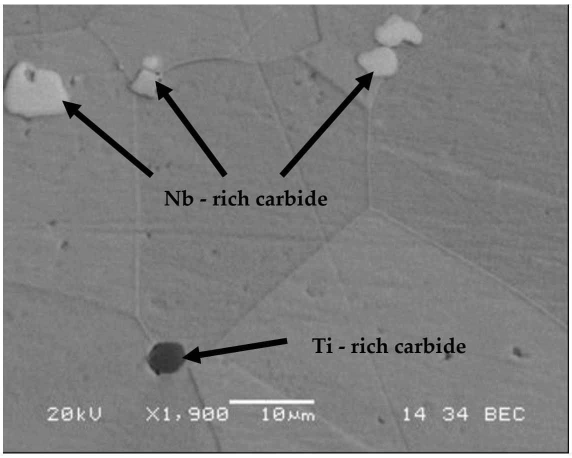

FIG. 1 SEM IMAGE OF WROUGHT IN 718 PRE-WELD HEAT-TREATED AT 1050°C/1HR/AC

As earlier stated, both the mechanical and metallurgical factors played vital roles in susceptibility of welds to HAZ cracking. One important metallurgical factor widely accepted to influence resistance to weld cracking is hot ductility, which is primarily investigated in the current work. Previous work have also showed that increasing weld heat input leads to reduction in the overall cracking susceptibility in superalloy welds [Vincent 1980, Thompson 1998, Richard 1994, Idowu 2007], however, the mechanism through which high heat input causes reduction in the extent of intergranular HAZ cracking has not been fully studied and comprehended. Therefore, to further understand the influence of weld heat input on HAZ cracking in alloy IN 718, the hot ductility of the alloy was evaluated by subjecting Gleeble specimens to tensile loading, first after 0.5 seconds and 3 seconds at test temperature 1160°C and the result is presented in Figure 2. In general, the higher the weld heat input the longer the time the HAZ material spent at the peak temperature, that is, the highest temperature attain during welding. A major consequence of intergranular melting in nickel-

base superalloys is loss of material ductility under tensile loading [Lin 1993]. The ductility of IN 718 Gleeble sample is initially very low (2.4%) for the holding time of 0.5 seconds, which is in agreement with reported poor ductility of solution heat treated IN 718 alloy at 1160°C by previous investigators [Vincent 1980, Vishwakarma 2008]. In contrast, however, upon increasing the holding time of the Gleeble sample during the hot ductility test from 0.5 seconds to 3 seconds, which is similar to increasing the magnitude of the heat input on the Gleeble specimen, an improvement in ductility from 2.4 % to 17 % was observed (Figure 2).

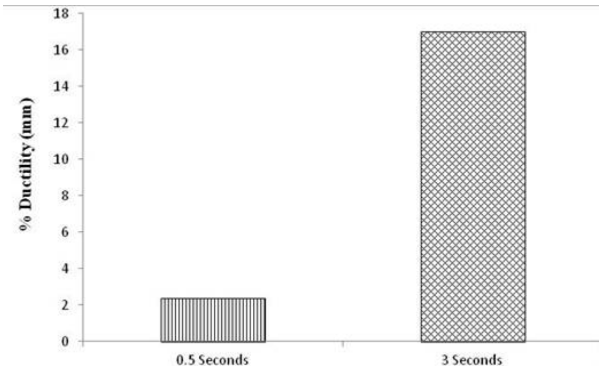

FIG. 2 VARIATION IN HOT DUCTILITY OF ALLOY IN 718 WITH INCREASE IN HOLDING TIME AT PEAK TEST TEMPERATURE 1160°C

Previous studies have shown that an important way to confirm grain boundary liquation is to perform fractography study on the associated fissured surface. Scanning electron microscopy study of the fracture surface of the Gleeble hot ductility specimens confirmed brittle intergranular failure in specimens tested at a peak temperature of 1160°C with 0.5 seconds holding time (Figure 3a). Higher magnification examination of the grain surfaces revealed regular roundish surface features all over the grain facets (insert in Figure 3a) which have been reported to be indications of re-solidified intergranular liquid phase [Wang 1991, Qian 2003]. For clarity and comparison, examination of the fracture surface of hot ductility specimen tested at 1160°C for 3 seconds is shown in Figure 3b. The specimen exhibited a ductile transgranular failure mode with shear stretch marking in contrast to the intergranular brittle failure features observed in specimens held for 0.5 seconds at test peak temperature 1160°C (Figure 3a). Therefore, it is reasonable to infer that the noticeable improvement in ductility with an increase in holding times at the peak temperature is one of the vital contributing factors aiding the reduction in extent of weld cracking with increase in heat input in superalloy IN 718. Aside from poor hot ductility induced HAZ cracking that occurs during welding of superalloy, the magnitude of stresses and strains generated during weld cooling is another factor that could influence the extent of the HAZ cracking. During welding, besides the effect of mechanical restraint, generation of thermally induced stress and associated strain is unavoidable, because of the differences in the rates of expansion and contraction of different regions in the HAZ caused by the thermal gradient induced by welding operation. The magnitude of such thermally induced welding stress is generally influenced by HAZ temperature gradient. High heat input welds are known to exhibit shallow gradient of temperature in the HAZ during welding compared to the steep HAZ thermal gradient that characterises low heat input welds.

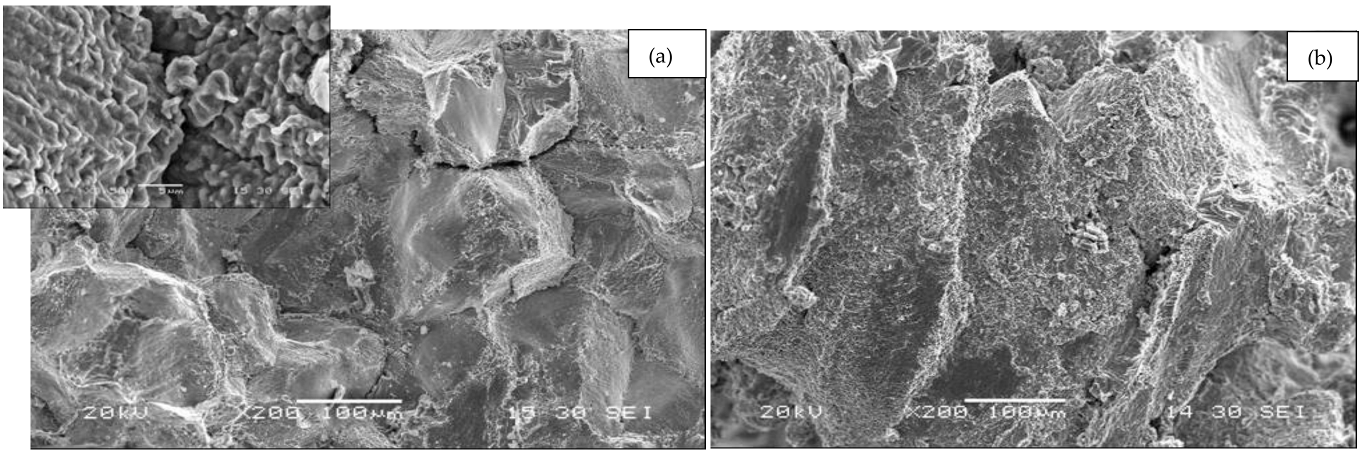

FIG. 3 SEM FRACTOGRAPH OF GLEEBLE SPECIMEN TESTED A) AT 1160°C HELD FOR 0.5 SECONDS AND B) AT 1160°C HELD FOR 3 SECONDS

In this study, an additional investigation, using numerical simulation, was performed to enable a better understanding of the dependence of the magnitude of HAZ cracking on the welding heat input. In its basic form, heat input, Q_1, is dependent on the power of the welding heat source, P, and welding

speed, ν, through the equation;

$$Q_1 = k\frac{P}{v}$$

where k is a constant. Accordingly, the magnitude of welding heat input can be varied by either changing the laser power or welding speed. In the present numerical simulation study, both the laser power and welding speed were varied, exclusive of each other, to analyze the effects of heat input on weld characteristics during laser beam welding. Also, cracking generally occurs when significant amounts of thermal strains are generated during weld cooling. Hence, the rate at which thermal strain develops at different weld locations, thus, become important in evaluating the propensity to HAZ liquation cracking. The numerical model, developed in this work, was used to calculate the strain rates generated at various locations along the weld fusion boundary and determine how these values are influenced by welding speed and laser power. Figures 4 and 5 show numerically calculated variation of strain rates along the weld profile for different values of welding speed and power, during the laser welding. The abscissa shows the distance from the weld top surface to the root of the weld, along the weld fusion boundary. The left side ordinate shows the distance from weld centerline, along the weld top surface (a sketch of a typical welded joint and distances is shown in Figure 6), while the right side ordinate shows the strain rate. Detailed analyses of the results show that while increasing welding speed caused a significant increase in strain rate, an opposite effect is produced by increasing power. The two trends show the same influence of heat input on the rate at which thermal strains are generated along the weld profile, starting from the weld surface to the weld root.

A careful study of the calculated results, presented in Figures 4 and 5 shows another interesting behaviour in terms of variations of the strain rate along the weld profile. A reverse in the strain rate behaviour occurs at the "neck" region of the nail-shaped weld profiles. The strain rate initially decreases from the weld surface to the "neck" region, however, starting from the "neck" region, the rate increases towards the root of the weld. Experimental observation reported in previous studies showed that the HAZ liquation cracks concentrate around the "neck" region of welds [Krenz 2009, Idowu 2007]. The strain rate gradients within the "neck" region in welds produced by different welding conditions were numerically calculated to compare the propensity to cracking. As shown in Figures 7 and 8, increase in heat input, either by reducing the welding speed or increasing the power, reduces the magnitude of the strain rate gradient which is in agreement with previously reported experimental finding in IN 718

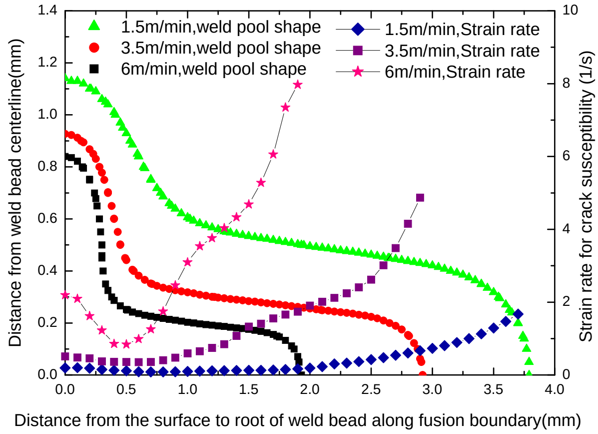

FIG. 4 STRAIN RATE VARIATION ALONG FUSION BOUNDARY OF LASER WELDS PRODUCED AT DIFFERENT VALUES OF WELDING SPEED AT CONSTANT POWER.

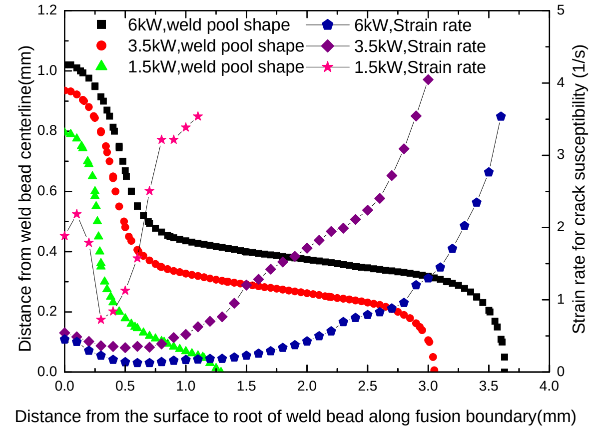

FIG. 5 STRAIN RATE VARIATION ALONG FUSION BOUNDARY OF LASER WELDS PRODUCED AT DIFFERENT VALUES OF LASER POWER AT CONSTANT SPEED.

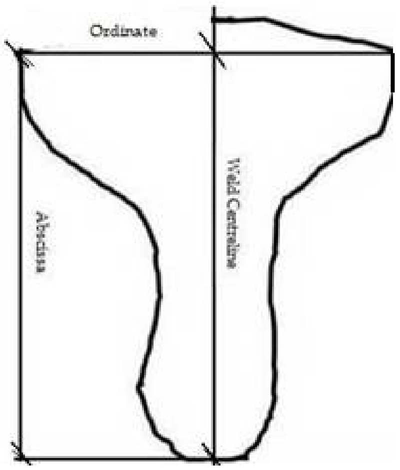

FIG. 6 SKETCH OF A TYPICAL WELDED JOINT SHOWING WELD CENTRELINE, ABSCISSA AND THE ORDINATE DISTANCES

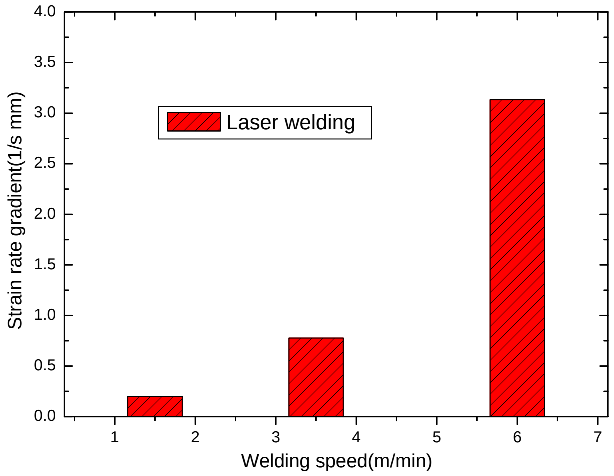

FIG. 7 STRAIN RATE GRADIENT IN THE "NECK" REGION OF LASER WELD USING DIFFERENT WELDING SPEEDS AT CONSTANT POWER.

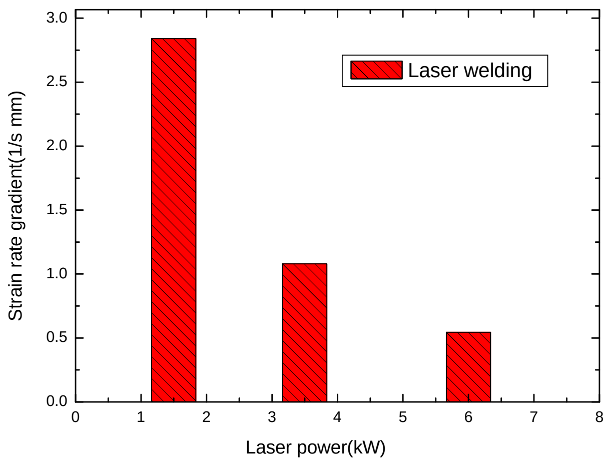

FIG. 8 STRAIN RATE GRADIENT IN THE "NECK" REGION OF LASER WELD USING DIFFERENT LASER POWER VALUES AT CONSTANT WELDING SPEED.

alloy [Krenz 2009]. Therefore, the strain rate gradient within the "weld-neck" region appears to be an important mechanical driving factor that influences the occurrence of the HAZ liquation cracking during application of low heat input laser beam welding of superalloys.

Conclusions

Physical and numerical simulations were performed in order to better understand how weld HAZ liquation cracking in a nickel-base superalloy, IN 718, is influenced by the magnitude of welding heat input. Gleeble thermo-mechanical simulation indicates that increase in heat input minimizes the extent of the hot ductility damage in the material due to the longer time available for re-solidification of non-equilibrium intergranular liquid that otherwise embrittles the alloy. Also, numerical calculations show that thermally generated strain rate gradient within the "weld-neck" region, which appears to be a major mechanical driving factor that influences HAZ cracking during the laser beam welding, increases with reduction in heat input. Therefore, decrease in weld HAZ liquation cracking is attributed to improved material hot ductility coupled with reduced thermally induced strain rate gradient that is generated during weld cooling.

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